Review Article

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Design and analysis of timber-concrete-based civil structures and its applications: A brief review

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Abstract: Builders, designers, and the research community are becoming interested in incorporating timber and concrete based composite structures because they effectively integrate the structural qualities of timber and concrete. The structure's stiffness, ductility, and load capacity are all affected by the quality of the timber connections used in construction. However, timber-concrete-based structures are limited due to a lack of design knowledge and the brittle failure behaviour of timber under shear or tensile loading. Experimental, numerical, and analytical methods have been proposed in the literature, and the key parameters influencing the performance of timber-concrete structures have been discussed. This study addresses the current challenges in designing timber-concrete connections and their failure modes and suggests simple performance-based analytical models that determine the failure mode. It looks at some of the best numerical design methods used in the past and tries to determine the best way to use timber as a possible way to use safe design principles for timber–concrete composite structures in the future.

Keywords: timber-concrete composite, non-linear analysis, shear connections, failure modes, architectural characteristics

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1 Introduction

Connections play a crucial role in the behaviour of a structure, not only concerning cost or their effect on the overall structural behaviour but also regarding safety. Some well-known structural collapses, such as the Siemens Arena and the Jyväskilä Fair roof, were caused by the failure of the connections [1]. There are infinite architectural possibilities and buildings based on technical and cultural practices, but the use of timber in construction has been of interest to the industry. Timber has attractive physical qualities, such as high strength-to-weight ratio, low environmental impact, ease of handling, and use for prefabricated structures. These qualities have made timber a favourable attribute in construction projects. Although a ductile connection failure is desirable, a brittle failure in the timber itself is possible, making timber structures vulnerable to dangerous circumstances or catastrophic construction failures [2]. As a result, there is a need to look into developing design models that allow designers to use timber as a safe building material for various structures.

Using timber framing in construction has traditionally resulted in plastic deformation, typically paired with redundancy, such as nail fastening plywood sheathing to timber studs [3]. Cross-laminated timber (CLT) is becoming an increasingly popular building material worldwide as it has high stiffness, resistance to in-plane tension, better compression resistance, and an effective energy dissipation capability [4]. Recent research indicates that adhesive bonding offers several advantages, such as uniform stress distribution along the connection, which results in less localised stress [5–9]. Brunner *et al.* [8] used a single flexible adhesive layer instead of a typical stiff adhesive in the beam cross section. The experimental investigation determined that beams made using one adhesive layer were more substantial than the control beams, defying theoretical predictions. Angelidi *et al.* [10] experimentally investigated double-lap timber joints' tension and compression properties using a brittle epoxy and a ductile acrylic adhesive. They concluded that acrylic-bonded joints showed a non-linear load-displacement response in tension, whereas epoxy-bonded joints showed a relatively linear load-displacement response up to brittle failure. The ultimate loads in acrylic-bonded joints were much higher than those of epoxy joints.

The timber–concrete composite (TCC) connection significantly impacts the behaviour of the TCC structural component [11]. The optimal connection is strong enough to support shear forces between the two members, rigid enough to allow only minimal slide, and ductile enough to prevent brittle failure of the connection. There have been several connection methods designed, each with its unique benefits. In timber engineering, dowel-type connections are prevalent, but existing design guidelines are simplistic and primarily based on empiricism. This prevents the most efficient use of connections, which is necessary to design cost-effective timber buildings. Wilkinson and Augarde [12] investigated 3D-numerical modelling to determine the slip modulus of single- and double-shear dowel-type connections. They concluded that the proposed numerical model significantly overestimates the slip modulus in single- and double-shear connections employing timber dowels. The most brittle connections are those with notches, whether they are rectangular, or round, with vertical or inclined sides. The placement of a steel fastener (dowel or screw) into the notched connections significantly increases the ductility of the connection [13]. In TCC buildings, glued connections are a form of adhesive connection. Glued connections have better mechanical properties like higher rigidity, lower deformations, and greater load-bearing capability. They also improve the TCC structure's resilience and sustainability by obviating the necessity for mechanical fasteners, which can corrode over time. Pizzo *et al.* [14] proposed a new specimen geometry to measure the shear strength of both glue line and solid timber with the same test specimen to minimise the impact of wood variability. Finite element modelling (FEM) revealed that the stress distribution had a negligible effect, but the compressive prestress on the timber adherents resulted in reduced resistance. In summary, TCC structures can be used in various engineering applications, including building floors, constructing bridges, roofs and walls, marine infrastructures, and industrial facilities. TCC structures exhibit a combination of characteristics such as durability, strength, and sustainability, making them a viable alternative to traditional construction methods. The strength and stiffness qualities of the shear connection between the members significantly impact the performance of a composite beam in terms of strength and stiffness [15].

Timber connectors with inclined tapping screws have a high slip modulus and can be used efficiently in composite beams. For linking timber with steel members, self-

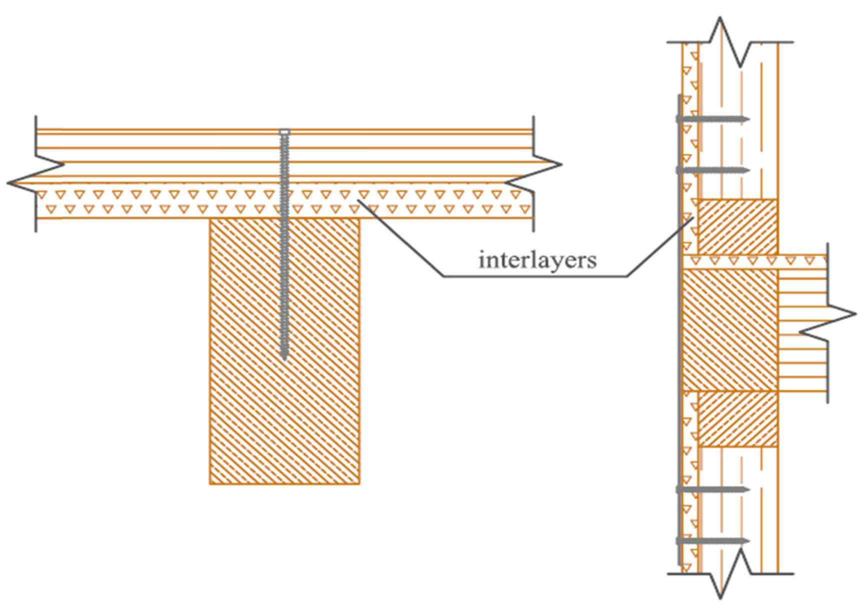


Figure 1: Representation of self-tapping screws' usage [3].

tapping screws can be used, as shown in Figure 1. Tomasi *et al.* [16] developed and proposed an approach for determining the load-bearing capacity and stiffness of screws that are positioned in an inclined position concerning the shear plane and subjected to shear-compression, shear-tension, or a combination of the two types of forces. A similar study by Girhammar *et al.* [17] proposed a model for dowel and withdrawal movements to predict the slip modulus of inclined screw joints in a shear-tension mode in timber-to-timber connections valid in the elastic or linearised stage of the load-slip relationship. Assuming that the screw was rigid and that withdrawal stresses were uniform, the model can estimate the influence of lengths and optimal inclination angles for dissimilar geometries of the two components connected.

The primary benefit of employing a timber concrete composite is that the thickness of the concrete component will be lower by 50% when compared to a conventional concrete slab, thus reducing the carbon footprint and self-weight of the building. This study aims to discuss the difficulties associated with using timber as a construction component, provide clarification on the type of failure in timber connections used in construction structures, and highlight the best practices based on experimental and numerical methods. An attempt has been made to highlight critical design considerations and determine potential solutions to implement safe design principles.

An outline of the remaining content of this study is as follows: Section 2 discusses the mechanical performance of different TCC connections under bending and shear conditions. Sections 3 and 4 present the existing analytical and Finite element (FE) methods to analyse the TCC connections, explicitly including the uncertainty describing the parameters in constitutive models for shear connections, concrete, and timber. FEMs predict that using timber connections can enhance the load-bearing capability of timber structures, but these connections exhibit either ductile or brittle failure. Hence, Section 5 discusses the different modes of failures in TCC connections. Based on understanding different connections and their failure modes, Section 6 is dedicated to different applications of TCC structures and discussions focusing on existing designs. Section 7 describes the need for a sustainable and renewable solution in the construction industry to reduce energy consumption and CO_2 emissions and create healthier spaces. Finally, Section 8 represents the conclusion.

2 TCC structures

Timber, concrete, and shear connections combine to form TCC structures. TCC structural elements are typically horizontal, one-way spanning elements subjected to uniaxial bending. Compared to pure concrete structures, TCC systems have better flexural behaviour, fire resistance, and acoustic separation while reducing self-weight and providing superior seismic performance [18]. One of the primary benefits of adopting a TCC is that the concrete component depth may be lowered by about 50% when compared to a conventional concrete slab, lowering the carbon footprint and the structure's self-weight [19]. Furthermore, timber can function both as a structural element and a formwork, reducing the need for formwork and supports and allowing more significant prefabrication. Timber wood is typically placed on the lower side of the element undertaking the tensile stresses, and concrete is on the upper side, resisting the compressive stresses. While some TCC structural elements with concrete placed on the bottom side [20] and even some TCC wall systems [21] are also available in the literature. All of this makes TCCs an appealing choice for traditional reinforced concrete structures. Over the last two decades, TCC members have seen growing use, prompting substantial study into analysing systems experimentally, numerically, and analytically resulting in more explicit methodologies and design options for TCC structures [22–24].

2.1 TCC mechanical principles

Different research groups have conducted experiments on various local (joints or connections) and global (laminated veneer lumber: LVL, sawn timber, and glulam) elements of TCC systems. TCC structural elements are typically simply supported, one-way-spanning slab or beam floors exposed to vertical external loads resulting in a positive bending moment [25]. TCC flooring with notched connections uses the complementary material qualities of timber and concrete, demonstrating a high level of a composite system between the two layers. Zhang *et al.* [26] presented an experimental study with timber-panel–concrete composite floors with reinforcement in the notched connections to reinforce the concrete and limit the cracking of concrete. The experimental results determined that the reinforced notched connections increased the ultimate bending stiffness and load-carrying capability of the composite flooring.

The results of a long-term experiment on a 6 m long TCC beam with a glued re-bar connection were reported by Ceccotti *et al.* [27], and it was determined that deflection mainly increased during the first 2 years, whereas slip increased throughout the testing period. Mudie *et al.* [28] worked with full-scale multi-joist TCC floor specimens made of concrete, hardwood, and LVL joists connected

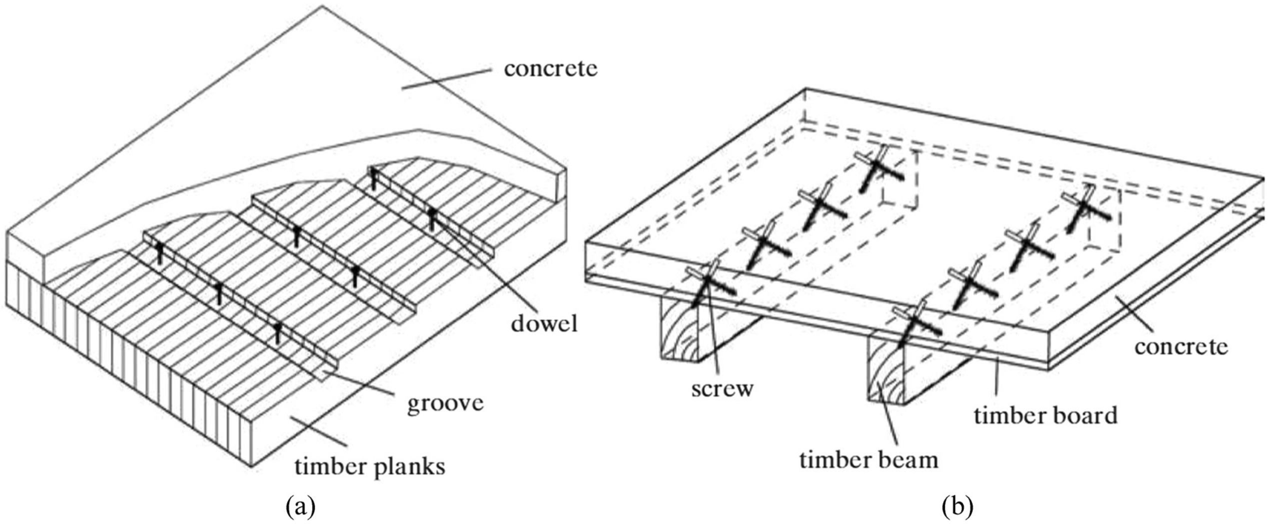


Figure 2: TCC flooring design: (a) slab-type floor and (b) beam-type floor [25].

by expanded steel mesh shear connectors. The results demonstrated that steel mesh plates were efficient shear connectors in TCC floors (Figure 2). The connectors showed significant slipping stiffness, strength, and ductility after failure. In a simply supported design condition, Shi *et al.* [29] conducted a series of experimental analyses using four-point bending tests until collapse failure occurred. Test results showed that TCC beams with steel plate and screw connections had better structural performance, with the prestressed specimens' flexural capacity increasing by about 110%.

Many research articles exist discussing the performance of TCC structures under bending. Boccadoro *et al.* [30] presented experimental research on TCC elements constructed for LVL with notched connections. This experimental effort aimed to verify an analytical model for the ductile design of a composite part based on the assumption that a plastic compressive failure mode of LVL within the notches would be the prevailing failure mode. Yeoh *et al.* [31] discussed the four-point bending and short-term collapse testing results on LVL–concrete composite floor T-beams. The connection options explored include triangular and rectangular notches cut into the timber, strengthened with coach screws, and modified toothed metal plates pushed against the LVL joists' edges. The triangular notch was a feasible option since it accommodated more connections and was easier to cut than the rectangular notch. Shi *et al.* [32] presented the findings of long-term experiments on

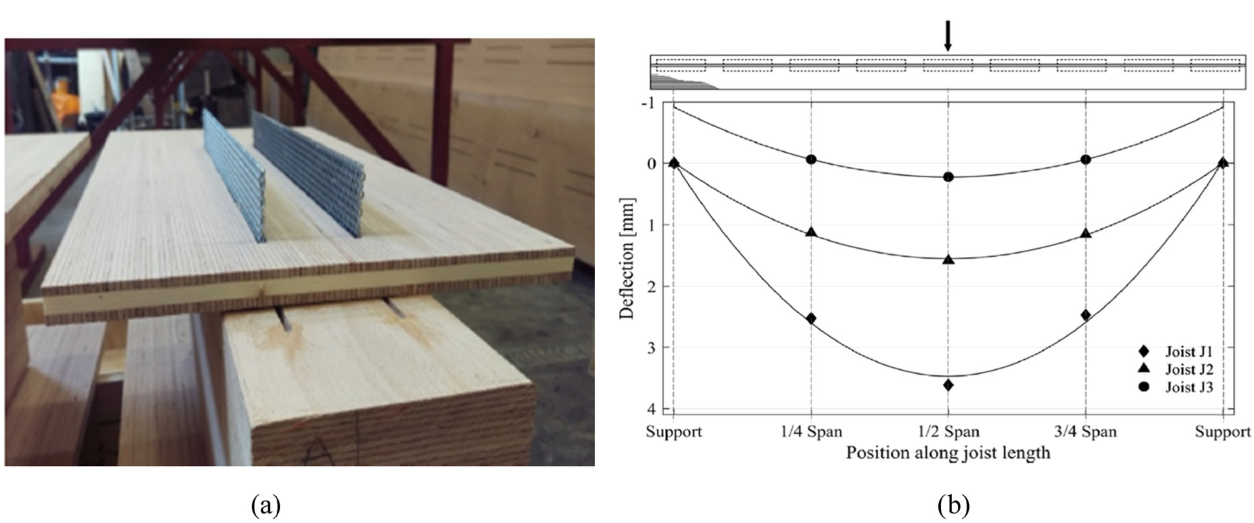


Figure 3: (a) Steel mesh connector and (b) deflection profiles at 20 kN mid-span test load [28].

TCC beams using a novel manufactured steel plate connection system consisting of screws and steel plates implanted in concrete slabs, providing a dry-type connection as shown in Figure 3. All the specimens showed minimal changes in strain, mid-span deflection, and relative slip over time, without degrading further. The results indicate that TCC beams with the new steel plate connecting method have better long-term performance.

2.2 Description of TCC connections

TCC has a significant impact on the behaviour of concrete structural components. The TCC connections' mechanical behaviour directly affects the composite system's most essential mechanical characteristics, such as deformation, load-carrying capacity, and stiffness. The ideal connection has sufficient strength to transfer shear forces between the two materials, is sufficiently rigid to permit only minimal slippage, and has adequate ductility to prevent the brittle breakdown of the connection. Many authors have addressed the ductility needs of composite systems with semi-rigid connections, emphasising steel–concrete composite structures [33]. However, significant discrepancies exist for timber–concrete hybrid systems, owing to the brittle nature of wood as compared to steel. Numerous timber-concrete connections with highly varied mechanical characteristics result in partial contact, *i.e.* semi-rigid connections, or complete interaction with no-slip, *i.e.* rigid connections. An effective connection must enable maximum shear stress transfer between timber and concrete connections with minimal slide. Figure 4 shows the stress distributions over the TCC cross section for each possible connection condition.

Dowels, inclined screws, nails, and other metallic connections are examples of dowel-type fasteners. Dowel-type fasteners, except for inclined screws, constitute the least stiff and most ductile connecting mechanism. Various research works and studies dealing with the analysis and design of TCC connections have been established during the previous few decades. The load-bearing capability of dowel-type fasteners is thoroughly examined in the literature [34].

Notched connections are mostly brittle, which are round and rectangular, with vertical or inclined sides. Including a steel fastener into the indentation considerably improves the ductility of the notched connection. Various research papers from the literature have addressed the performance of notched connections extensively, [35] and existing experimental test findings on notched connections were collected and evaluated in a Short-Term Scientific Mission conducted by Kudla [36].

Brittle failure is observed when the applied load is beyond the strength of glued connection, making them extremely rigid and allowing nearly complete composite performance. Glued connections ensure consistent shear force dispersion and can connect timber and concrete slabs [27].

Plate designs for nail plate connections vary; one option is a plate with a bottom half that acts as a nail plate and is positioned between two timber beams and an upper section that acts as a perforated plate. Such a connection can be designed as "an integral plate and nail plate system," where the plate is designed so that it serves both functions simultaneously [37].

2.3 TCC under shear loading condition

The comparable material properties of timber and concrete are combined in TCC floors with notched connections, resulting in a high level of composite interaction between the two layers. However, because of the low tensile strength of concrete and the concentration of stress at the notched corners, cracks frequently form in concrete at the service load level, causing brittle shear failure of concrete notches before the bending strength of timber or concrete is achieved. Ling *et al.* [38] evaluated the shear performance of three types of shear connectors, consisting of a steel component secured to timber by screws and glued-in rods (GiRs) for TCC beams, using single-shear testing. With a shear capacity of 158.92 kN, the I-shaped steel shear connections supported by GiRs had the maximum shear capacity. Also, the folded steel plate shear connections with GiRs and screws had a maximum slip modulus of 38.41 $kN{\cdot}m^{-1}$. Shi *et al.* [39] presented the findings of long-term testing on TCC beam specimens in an uncontrolled indoor environment, where the long-term loads absorbed by the beam specimens were roughly 18.8% of the short-term flexural capacity. Figure 5 shows the different types of floor systems being adopted using TCC. Experiments were done to examine the effects of connection geometry, the presence of self-tapping screws in the connection, and the orientation of the wood on the shear characteristics of notched connections of glued laminated wood panels [40].

2.4 Summary for TCC

A TCC component can reduce concrete thickness by about 50% compared to a standard concrete slab, minimising self-weight and carbon footprint. Also, TCC beams with the steel plate connecting method have better long-term

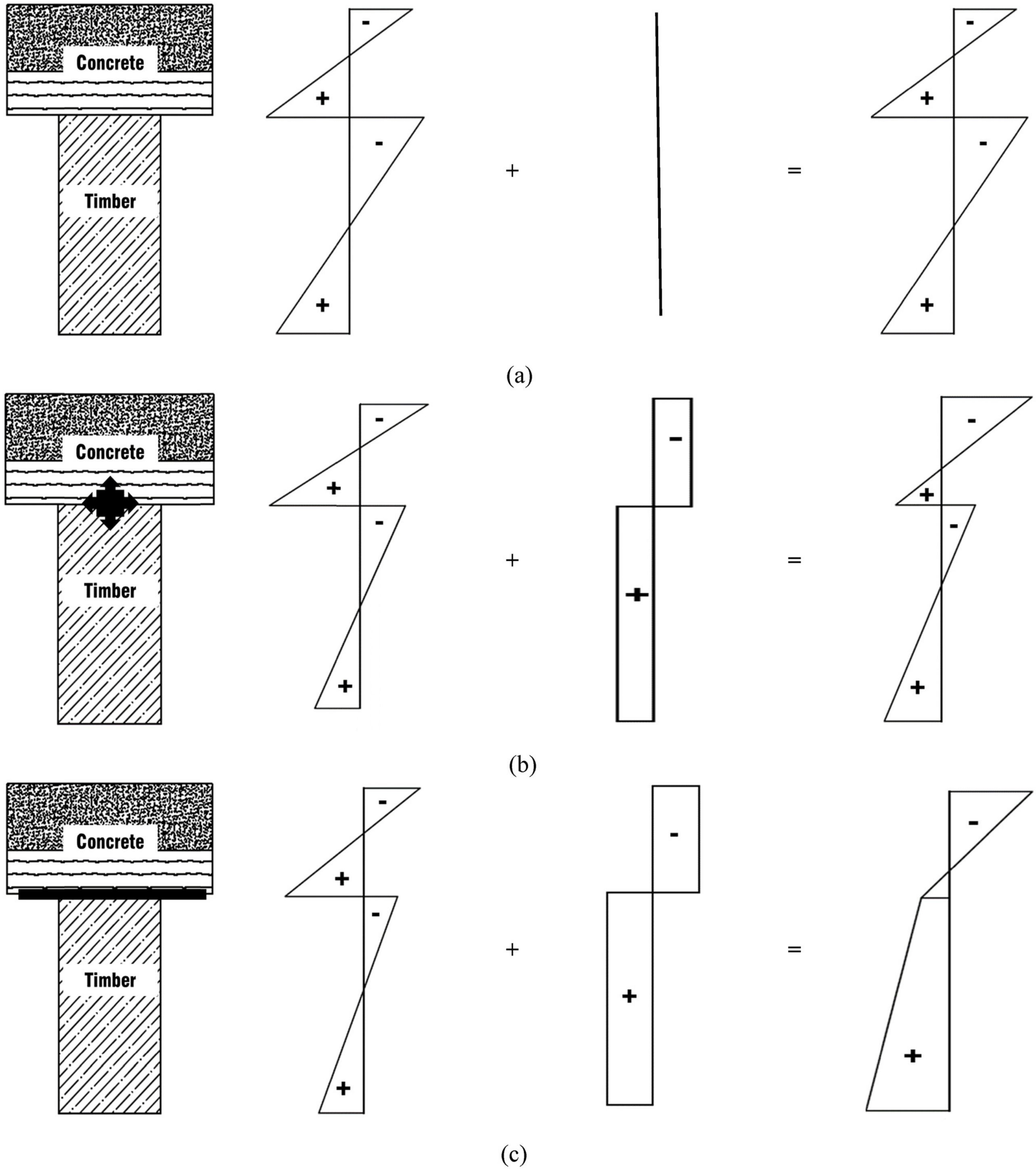


Figure 4: Representation of stress distribution over the TCC cross section (where "+" represents tensile stresses and "–" represents compressive stresses) [33]. (a) Without connection, (b) semi-rigid connection, and (c) perfectly rigid connection.

performance. An efficient connection must transmit maximal shear loads between the timber and concrete connection while allowing for little slippage. It can be concluded that connections with timber in the longitudinal direction had much higher strength and stiffness than those in the transverse direction due to the anisotropic structure, but this discrepancy can be resolved by using self-tapping screws to enhance the transverse strength of these connections.

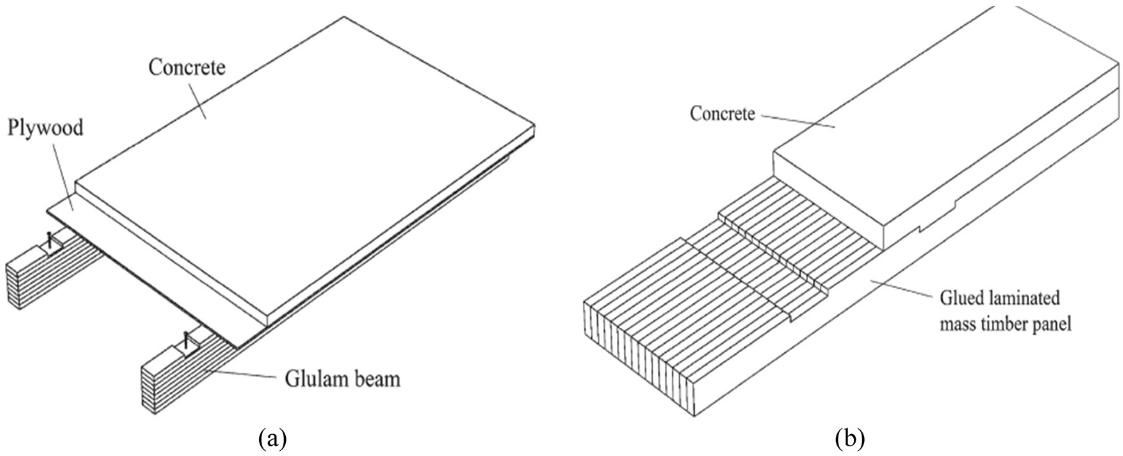


Figure 5: Timber-composite floor systems [40]. (a) T-beam type and (b) mass timber panel.

3 Timber connection – analytical investigation

The majority of composite beam models were developed to deal with the continuous link between two layers. The Eurocode 5 approach is the sole analytical method for TCC beams that can be found in design standards that commonly deal with the γ-method, which was proposed by Möhler [41]. The γ-method is based on the assumption that a simply supported beam is exposed to a sinusoidal distributed load with a sinusoidal deflection. To account for the semi-rigidity of the shear connections, an effective bending stiffness of the beam can be added by assuming a homogeneous interaction between timber and concrete. Girhammar [42] determined a simplified approximation method considering effective beam span instead of actual span depending on the boundary conditions. Despite the widespread adoption of continuous bond models, shear loads are only transferred at discrete points when notched connections are employed to join two layers in the TCC system, and the spacing of notches is frequently too great to use continuous bond models. Thus, if a continuous bond is assumed, the distance between discrete connectors should not exceed 3% of the beam span [43–45]. The document of the revised Technical Specification on timber concrete composites [46] includes formulae for calculating the slip modulus of connections at the timber–concrete interface. It states that the slip modulus of a concrete-timber connection can be conventionally approximated by doubling the K_s and K_u values determined by Eq. (1)

Wood-based panel-to-timber and timber-to-timber connections.

$$\left.\begin{aligned} K_s &= \frac{d}{23}\rho_m^{1.5} \\ K_u &= \frac{2}{3}K_s \end{aligned}\right\}, \tag{1}$$

where K_s is the slip modulus of a connection when it is designed to operate at its serviceability limit condition, K_u is the slip modulus of a connection intended for use in ultimate limit state design, and ρ_m is the mean density of the timber element.

Particularly for dowel-type fastener connections, the mean slip modulus for ultimate limit states K_u may be estimated to be two-thirds of the slip modulus for serviceability limit K_s as represented in Eq. (2).

$$K_s = \begin{cases} 2\dfrac{d}{23}\rho_m^{1.5} & \text{for dowels, bolts, screws, and nails} \\ 2\dfrac{d}{30}\rho_m^{1.5} & \text{for Nails without predrilling.} \end{cases} \tag{2}$$

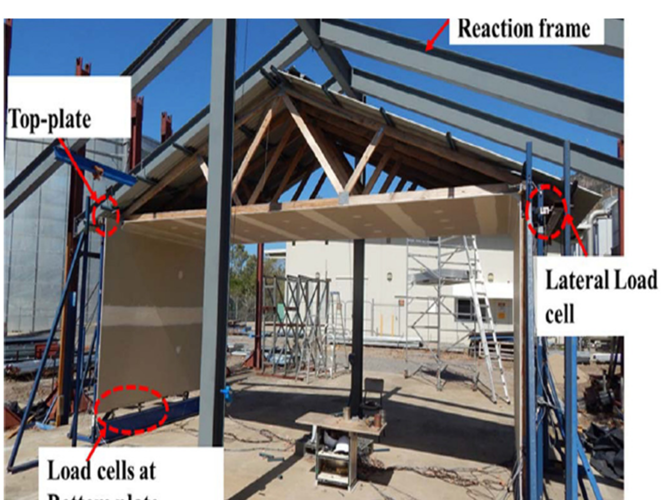
The connecting system used is critical since it affects both structural performance and cost. The strength and stiffness qualities of a composite beam are highly dependent on the shear connection between the components. As a result, additional attention must be paid to the selection of robust yet reasonably connected solutions. Shear connections should be sufficiently rigid to guarantee that timber and concrete elements function in concert. Di Nino *et al.* [47] employed inclined elastic beam on an elastic foundation model to forecast the slip modulus of timber-to-concrete connections with the interlayer. De Santis and Fragiacomo [48] proposed a similar strategy for extending the model to timber-to-timber and steel-to-timber linkages where the elastic beam serves as a substitute for the screw, while the surrounding timber is represented by two independent springs. It needs to be noted that even in the situation of perpendicular screws without interlayers and an FEM for screwed connections that are predictive based solely on the mechanical parameters of wood and concrete, Eq. (2) predictions were proven to be inaccurate [49–53].

4 Computational simulation of timber connections

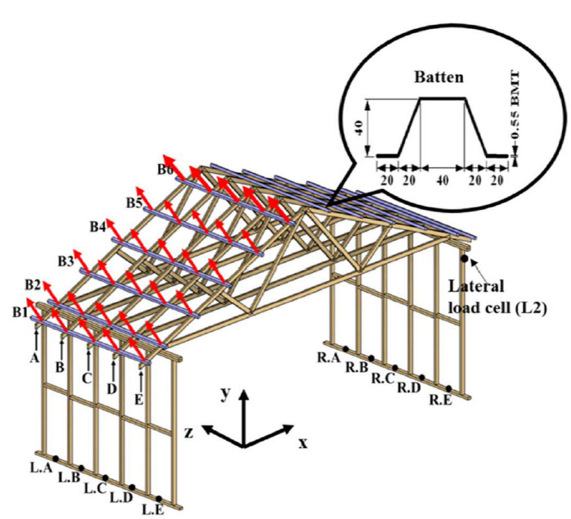
Timber materials exhibit a variety of characteristics, including brittle, semi-brittle, and ductile in tension/shear, parallel-to-grain compression, and perpendicular-to-grain compression. Thus, they can be typically described as highly anisotropic non-linear materials in three mutually orthogonal axes. Full-scale testing is the most reliable approach for evaluating the performance and structural reaction of timber-framed buildings, but it is seldom used due to the considerable cost and time required for the experiment. Full-scale testing, on the other hand, necessitates a careful design and the placement of equipment without affecting load transmission inside the structure. After being verified using the structural testing findings, effective FEMs may be used in combination with this structural testing to analyse the structural response of a variety of timber-based structures cost-effectively. Satheeskumar *et al.* [53] used ABAQUS to construct a 3D FEM model for a modern-day timber-framed house, where the assemblage consisted of structural and lining parts. Figure 6 represents the experimental prototype and the FEM under consideration. The FEM study of a timber-framed structure exposed to vertical, lateral, and horizontal loads resulted in satisfactory structural findings with a maximum deviation of around 15% from full-scale test results. Franke and Quenneville [54] presented a numerical model for simulating complicated failure behaviours like ductile behaviour, bearing failure under the dowel or supports, and the brittle failure of dowel connections in wood loaded perpendicular to the grain. For the numerical solution, stress singularities at the dowels, embedding failure, and a direct debonding of the wooden structure were taken into account, along with other failure mechanisms. Table 1 represents a brief description of the methodology adopted and the tools being utilised to simulate TCC under different conditions.

4.1 Numerical simulation for timber – concrete-based composite structures

Based on classical theories of plasticity, a mathematical model can be used for orthotropic and timber materials to determine their ductile behaviour [55]. A 3D non-linear FEM model to determine the mechanical behaviour of timber–concrete junctions is presented by Dias *et al.* [55]. In the study, an orthotropic yield criterion, *i.e.* Hill's criterion associated with isotropic hardening, was used, and it was observed that the numerical models overestimated the



(a)



(b)

Figure 6: (a) Full-scale test structure and (b) schematic representation of the frame and potential load location [53].

Table 1: Brief description of modelling methodology and tools utilised

Year	Ref.	Tool used	Modelling technique
2017	Satheeskumar *et al.* [53]	ABAQUS	Utilised 0.05% offset proof strains based on the initial tangent of stress–strain curve to account for the material non-linearity
2011	Franke and Quenneville [54]	ANSYS	Used contact element pairs with a cohesive zone material
2007	Dias *et al.* [55]	—	Isotropic behaviour – steel and concrete, orthotropic behaviour – timber
2022	Adema *et al.* [56]	ANSYS	Concrete elements consider the presence of reinforcing bars and are capable of cracking in tension and crushing in compression
2012	Zona *et al.* [57]	MATLAB	Euler–Bernoulli beam theory applies to both components of the composite beam and the deformable shear connection
2013	Raftery and Harte [58]	ANSYS	Theory of anisotropic plasticity to account for plastic behaviour of the material in the compression zone
2014	Khennane *et al.* [59]	ABAQUS	Ductile failure using theory of plasticity and brittle failure using continuum damage mechanics
2022	Tao *et al.* [60]	ABAQUS	1D model – two parallel plane beam elements with the connection of continuous non-linear spring elements 3D model – defined using elastic-plastic damage constitutive model of the timber

maximum load and the stiffness. Adema *et al.* [56] showed that the proposed analytical formulation produced a satisfactory estimate of the instantaneous deflection when compared to linear and non-linear short-term numerical models, regardless of the slab's boundary conditions. The procedure resulted in a 13% underestimation of the test findings. The short-term structural response of TCC beams is estimated by Zona *et al.* [57] using a non-linear FE frame model with deformable shear connection. The FEM was combined with a probabilistic analytic approach that accounts for uncertainty in the parameters that are characterised by the constitutive models for different components of the timber-concrete connections like timber, concrete, and shear connections. Raftery and Harte [58] proposed a numerical model to evaluate the use of fibre-reinforced polymer (FRP) plates to reinforce glulams constructed from Irish Sitka spruce of low grade, where the model takes into account both material and geometric non-linearities to forecast the stiffness, load-deflection behaviour, and strain distribution behaviour of the FRP plate. From Figure 7 it is evident that the computed load-deflection behaviour closely matches the experimental data, and the model accurately predicts the non-linear behaviour of reinforced beams.

4.2 Constitutive numerical modelling

Computational modelling is a powerful technique for optimising the performance of timber-based composite structural parts. Additional analysis of the timber composite structures can be performed using a numerical technique if the experimental behaviour can be efficiently modelled with greater accuracy. As a result, the expenditures associated with comprehensive testing programmes can be greatly reduced. Khennane *et al.* [59] proposed a three-dimensional material model based on applied classical flow theory, in which ductile failure is modelled using plasticity theory and brittle failure is modelled using continuum damage mechanics. The model was proven to be capable of forecasting the beginning of macroscopic cracks in wood specimens during tensile and bending testing. Figure 8 represents the comparison of load–displacement curves for tensile testing where the influence of softening during damage was evident. The computational efficacy of FEM for TCC beams in one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) were investigated by Tao *et al.* [60]. The ABAQUS user subroutines were used to define the 3D elastic-plastic damage constitutive model of the timber. The 3D model created utilising the user-defined material model accurately replicated the failure modes of the TCC beams, including timber fracture, end connection failure, and concrete slab fracture, and yielded more precise numerical results.

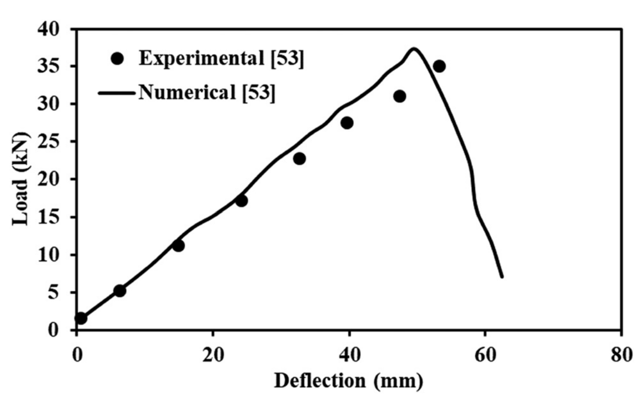


Figure 7: Load–displacement comparison [58].

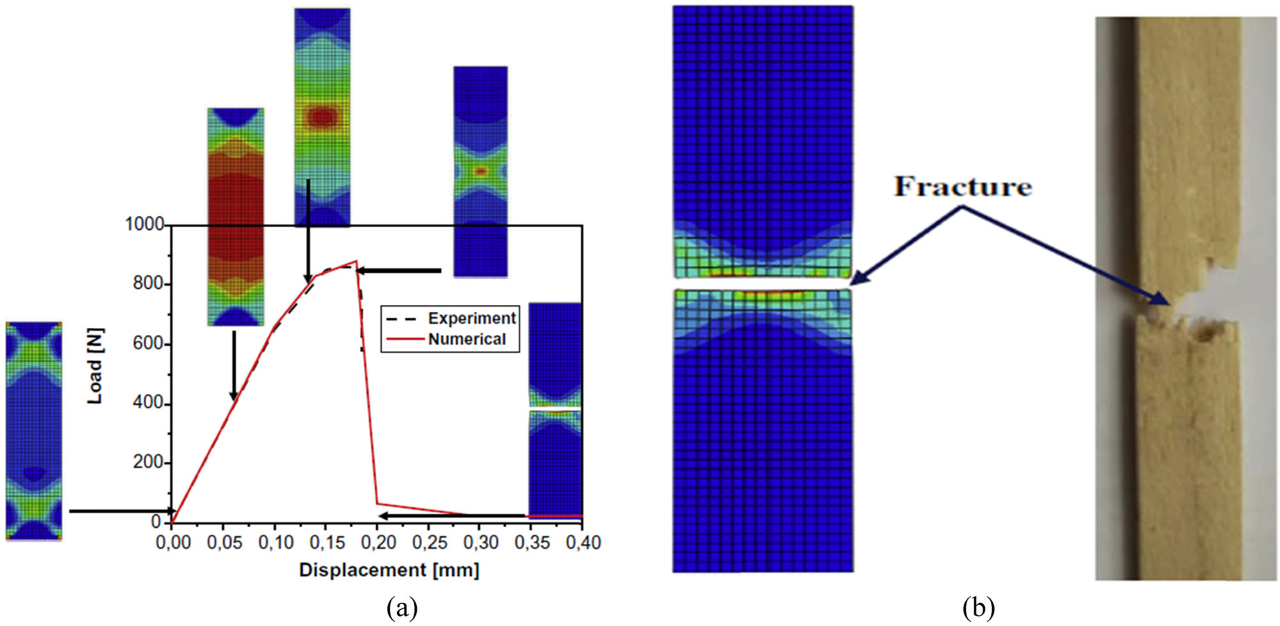


Figure 8: (a) Load *vs* displacement curve during tensile testing and (b) comparison of fractures sampled under tensile loading [59].

4.3 Summary on numerical modelling

The load-bearing capacity of timber frame constructions can be increased by using timber connectors. The interaction is incorporated into the structural analysis of typical timber frame systems using a FEM. All the interactions, connections, and different configurations can be modelled using FE methods and a good correlation between the experimental and numerical results has been observed in the literature. To summarise, the FEMs presented are not capable of identifying time-dependent properties of timber materials, which are extremely important in predicting various failure-related behaviours. Also, TCC interface's traction-separation properties are widely used for monotonic loading, but further research is needed to identify open-closure aspects of the interface during cyclic loading.

5 Failure in timber connections

Ductility is crucial in structural design to provide sufficient strength in TCC structures. As a result, the introduction of design models that allow designers to validate the resultant failure mode of their design is critical. In TCC buildings, screwed connections frequently fail because the screws pull away from the timber or concrete. Studied push-out-shear tests to analyse lag screw connections and determine the relationship between shear capacity and embedment depth in TCC. Lag screw connections were examined by Al Lawati *et al.* [61], and push-out-shear tests established the relation between shear capacity and embedment depth in TCC. The experimental findings reported that the embedded depth should be 7.33 times the lag screw diameter to prevent failure. Notched connections are created by cutting grooves in the timber to fit it over the concrete slab. The weakness in notched connections can arise from the compression of timber fibres surrounding the notch, leading to diminished strength and rigidity. The area around the notch can also be vulnerable to cracking and splitting, particularly under bending or tension forces. Shear failure of the concrete notch dominates the failure mechanism in TCC structures, and the length of the notch has a significant impact on shear behaviour [62]. Failure in glued-in connections can arise from deficient surface preparation, inappropriate adhesive selection or application, or moisture harm. If the bond between the timber and concrete weakens, it can lead to the separation of the timber component, decreased load capacity, and a decline in stiffness. Research indicates that adding rods and plates to glued-in timber-to-timber connections does not enhance the load-bearing ability linearly [63].

Fasteners larger than those usually examined in laboratories are used in construction connections. As a result, the strength of the joint can be determined by a brittle failure mechanism. Brittle failure should be assessed using dedicated models because it makes the designer aware of the danger of brittle failure. In the early 2000s, block-shear and row-shear models for brittle failure were introduced. Since both wood and steel fasteners plastically deform during embedment, only this method is termed ductile, whereas the other modes are termed brittle failure modes. It is commonly considered that plastic deformation can be prevented by ensuring an appropriate distance between fasteners. A centre longitudinal crack emerges along the row of fasteners during splitting, and it is commonly attributed to tension perpendicular to the grain. In his work, Jorissen [64] considered two possibilities for the relationship between the perpendicular-to-grain and parallel-to-grain stresses (wedge factor) and accounted for the development of shear stresses based on Timoshenko-beam on elastic foundation. Jockwer *et al.* [65] suggested revisions to the published works and considered that wedge factor $\beta_p = \frac{1}{7}$, which provided reasonable results. Hanhijärvi and Kevarinmäki [66] simplified the model proposed by Jorissen [64] based on fracture mechanics and proposed equations to account for the capacity of the connection's inner and outer components, and the total capacity is calculated as the sum of both. Splitting is a Mode I crack extension in terms of fracture mechanics since the new crack is formed by tension perpendicular to the applied load direction.

Similar to splitting, row-shear occurs along the row of fasteners; however, there are two parallel cracks instead of one in row-shear mode of failure. Row-shear, on the other hand, can be thought of as a mixed-mode crack extension between Modes I and II because the cracks are caused by both tension and in-plane shear stresses. Quenneville [67] proposed a geometrical model and stated that shortest distance between the fasteners triggers the failure of the rows in the connections. Furthermore, a new expression was proposed for intermediate conditions, in which the parameter "Φ" is derived from a set of equations that account for the various geometrical and material qualities of the timber member, as well as the specified failure criterion [68,69].

The tearing out of timber in the connecting area is the result of block and plug shear failures. This type of failure can be regarded as a failure of three separate planes, namely, the tensile plane H, the lateral shear plane L, and the bottom shear plane B. Block-shear connections are those that use large-diameter fasteners that extend through the entire timber member and do not activate the bottom shear plane B. Only the bottom and head planes are considered by Johnsson and Parida [70], since they experimentally determined that the lateral planes failed early compared to other planes and, thus, did not contribute to the connection capacity. The different failure modes discussed and the corresponding strength models proposed in the literature have been summarised in Table 2.

6 Characteristics and application of engineering timber

Green construction materials are currently causing a lot of concern, and heavy-polluting materials like steel and concrete are becoming increasingly unpopular. Timber is a sustainable material that has mechanical qualities that exceed the criteria for construction usage while also reducing carbon emissions into the environment [71]. Engineers and researchers are becoming more interested in timber buildings due to the necessity to meet high seismic performance requirements and to comply with the most recent global rules on environmental sustainability. As a natural structural material, timber is frequently chosen over concrete from an architectural standpoint. Therefore, timber components of TCC structural elements are typically kept exposed for aesthetic purposes.

Table 2: Proposals for brittle failure mode of connections loaded in the parallel-to-grain direction

Year	Ref.	Failure mode	Proposed model
1998	Jorissen [64]	Splitting mode	Strength: $2t\sqrt{\frac{G_f E_0 d \sin\alpha(b-\sin\alpha)}{b}}$
2017	Jockwer *et al.* [65]	Splitting failure	Wedge factor $\beta_p = \frac{1}{7}$
2008	Hanhijärvi and Kevarinmäki [66]	Splitting mode	Strength: hole and end $\frac{k_{conc}}{\beta_p}\frac{1}{s_{t90}}a_3 t f_{t,90}$
1998	Quenneville [67]	Row-shear failure	Strength: $2J_r n_c n_r t a_{L,min} f_v$, when $0.6 \le J_r \le 1$, function of n_r
2010	Jensen and Quenneville [68]	Row-shear failure	Strength: $\min\begin{cases}2n_c n_r t a_1 f_v\\ 2n_c n_r t a_3 f_v\\ 2\Phi t a_3 f_v\end{cases}$
2013	Johnsson and Parida [70]	Block-shear and plug-shear failures	Tensile head strength: $b_{net} t_{ef} f_{t,0}$ and bottom shear strength: $b_c L_c f_v$

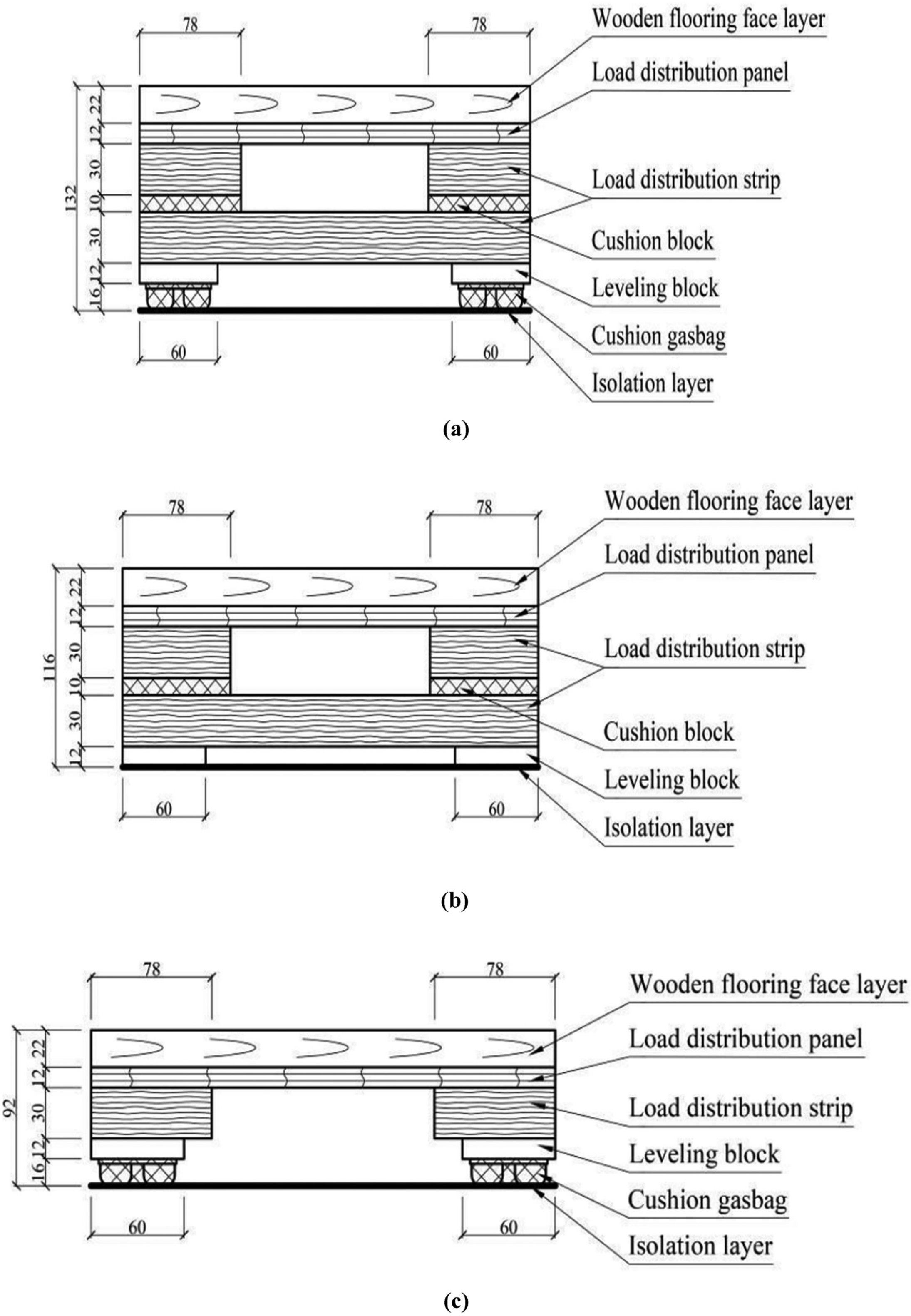


Figure 9: (a) Suspended structure with double-layer load distribution strip [72]. (b) Fixed structure with double-layer load distribution strip [72]. (c) Suspended structure with single-layer load distribution strip [72].

Table 3: Application of timber composite materials

Year	Ref.	Material type	Usage method	Application
2022	Jiang *et al.* [71]	CLT	Degree of freedoms of each vertex were analysed. Relationship between parameters were determined	Timber structure based on Yoshimura origami
2016	Sebastian *et al.* [73]	Hardwood	LVL concrete composite beam	Connections
2021	Yuhao *et al.* [72]	Single- and double-layer load distribution strip	Analysis of the natural frequency and damping ratio parameters	Wooden floor for gymnasium
2021	Felice *et al.* [74]	Glulam timber frame	Displacement-based design	Multistorey post-tensioned timber frame
2017	Bajzecerová [75]	CLT	Timoshenko beam theory and γ-method	Timber bearing structures
2008	Deam *et al.* [76]	LVL beam	Shear testing	Composite floor systems

TCCs are structurally efficient because they make use of the complimentary tension and compression-resisting capabilities of wood and concrete. Most shear-based connections between timber and concrete are made with dowels, rods, or slanted screws that are set into the wood and surrounded by concrete. Sebastian *et al.* [73] presented test results on beech LVL–concrete slab composite connections and externally indeterminate beams that were connected with connectors and concluded that in longitudinal shear tests, when the concrete was in compression, the connections had good slip stiffness and good shear strength, with ductile behaviour near the failure of the specimen. Yuhao *et al.* [72] investigated the dynamic properties of three gymnasium floor constructions under the assumption that the component materials' types, connections between layers, and specifications were all the same. Figure 9 shows the three types of gymnasium floor constructions used in the study, and it was determined that the double-layer load distribution strip (suspended structures) had the lowest damping ratio, indicating that it had superior impact buffering capability and resilience performance.

Felice *et al.* [74] investigated the experimental dissipation of energy dispersed by post-tensioned timber frame constructions with various anti-seismic technologies. The dissipative bracing systems model was shown to have a larger global energy dissipation than other models by over 25% at maximum intensities. Bajzecerová [75] considered Timoshenko's Composite Theory with Shear Deformations and the γ-method was summarised and examined for their effectiveness in the field of CLT concrete composite beams consisting of glued connections, and it was determined from the results that both the Timoshenko beam theory and γ-method produced the same results. Deam *et al.* [76] experimented to evaluate a variety of connection techniques that can be employed to determine the most efficient composite action between LVL support beams and a concrete slab, and from the results, it was determined that concrete plugs reinforced with a screw or steel pipe provided greater strength and stiffness when compared to other configurations. Table 3 summarises the different types of timbers used in civil structures and their corresponding applications.

7 Future scopes

Limiting global warming below 1.5°C is crucial to prevent the worst impacts of climate change. This demands net-zero greenhouse gas emissions by 2050. TCC structures, being a sustainable solution, combine the beneficial properties of both concrete and timber wood to provide a more durable and economical building material. TCC structures are essential in reducing the carbon percentage contributed in the construction sector. For example, Forte Living, constructed in 2013, became the tallest wooden apartment building in the world. According to reports, the building's carbon footprint was 22% lower than that of a similar reinforced concrete structure. As a result, future research will likely emphasise the following areas:

Sustainable structures: There is a scarcity of literature on the extended durability and sustainability of TCC structures. However, it is possible to enhance the environmental friendliness and longevity of TCC structures through the adoption of innovative construction techniques and the use of sustainable materials.

Design guidelines: The behaviour of TCC structures under various loading scenarios must be carefully investigated to assure their reliability and effectiveness. Researchers have conducted experimental and numerical research to examine the behaviour of TCC structures, but design guidelines for potential implementation are still needed.

Propose new structure combinations: Researchers must investigate and propose new TCC configurations that can be implemented in various applications. There is a need to conduct studies that explore the use of different types of timber, concrete materials, and their combinations to achieve optimal performance.

Cost-effectiveness: To ensure the practicality of TCC structures, it is crucial to examine their cost-effectiveness. This can be achieved by comparing TCC buildings with conventional building materials and exploring creative construction techniques.

The timber industry has expanded dramatically over the last decade, mainly to an increase in the usage of timber in construction. Overall, TCC research has a promising prospect since this material has the ability to produce sustainable, long-lasting, and aesthetic solutions for a variety of construction purposes. Dismantling, adaptation, and reuse are the best end-of-life disposal choices for timber structures. They will become more desirable when using large-section timber structures such as glulam beams, columns, CLT floor, and wall panels increase.

8 Conclusion

Various benefits of TCC constructions, such as sustainability, high strength, environmental friendliness, and durability, have contributed to the growing significance of TCC structural components in recent decades. TCC structural elements can decrease concrete thickness by 50%, lowering self-weight and carbon footprint. Moreover, using the steel plate connecting method in TCC beams enhances their long-term performance. The Eurocode 5 technique is the only analytical method for TCC beams specified in design standards. This necessitates the development of additional analytical methods for various TCC configurations and their validation against experimental data. TCC connectors boost the load-bearing capacity of frame structures. There is a need to study the bonding capacity by altering the timber-concrete bonding ability with different materials and connections. Regarding numerical investigations, the next logical step would be to include the fracture phenomenon and incorporate time-dependent properties of timber materials. These parameters are critical in the accurate prediction of various TCC failure-related behaviours. Timber connection failures exhibit ductile or brittle behaviour, resulting in lower load-bearing capacity in TCC structures. Plastic deformation can be avoided by maintaining sufficient spacing between connections. The depth of the notch is an essential architectural factor. As the depth of the notch is raised, the stiffness and strength of the connection improve. Screwed connections in TCC are also a popular method for joining timber and concrete elements. These connections perform significantly better in deformation capacity, ductility, and energy dissipation. On the other hand, the behaviour of screwed connections in TCC is complicated and depends on parameters, including screw diameter, spacing, and embedment depth. Furthermore, the long-term performance and durability of screwed connections in TCC systems require further research.

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